EFFECT OF PANEL TEMPERATURE ON A SOLAR-PV AC WATER PUMPING SYSTEM

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ABSTRACT

Panel temperature was monitored during a solar-AC water pumping experiment by the USDA-Agricultural Research Service, Bushland, TX. Using 6 years of average monthly panel temperature data, the solar panel performance during winter was estimated to be at rated power, but the solar panel performance during the summer was estimated to be only 93.5% of rated power. In addition, the water pumped on a hot day (36°C) was shown to be 7 to 10% less than on a warm day (20°C) – the entire performance loss was attributed to higher panel temperatures. Solar panel temperature was also shown to be dependent on wind speed which means solar-PV water pumping performance can also be affected by wind speed. In order that other locations besides Bushland can estimate the temperature effect on solar panel performance, an equation is derived in this paper for estimating the solar panel temperature.

1. INTRODUCTION

1.1 Background

Performance of solar-PV water pumping systems (1,2) and water purification systems (3) have been measured by the USDA-Agricultural Research Service (ARS) at their Conservation and Production Research Laboratory, Bushland, TX (16 km west of Amarillo, TX in the Texas Panhandle). In June 1995, we began collecting one-minute averaged data on a solar-PV AC water pumping system: 1 kW array with thin-film cadmium-telluride solar panels, smart controller which converted DC output from solar panels to either single or 3-phase AC electricity, single-phase and three-phase, 0.56 kW (0.75 hp) 230 V submersible motor, and a 12-stage 0.56 kW (0.75 hp) centrifugal pump. The data collected were:

1. global irradiance at solar panel tilt angle using a pyranometer
2. solar panel temperature using a thermistor attached to backside of solar panel
3. DC voltage and current between solar array and controller
4. AC voltage, current, and power between controller and pump motor
5. water pressure, an indication of total dynamic head
6. water flow rate using an electrical pulse flow meter

A procedure was adopted at the USDA-ARS laboratory to adjust the panel tilt angle at the equinoxes to stay within 13.5° of optimum tilt angle all year long resulting in only a 3% loss in energy from the sun at solar noon (e.g. COS(13.5°) = 0.972). Since Bushland is at 35° N latitude, the panel tilt angle was 25° from the horizontal during spring and summer and 45° during fall and winter (5).

While there probably was performance loss due to increased solar panel temperature on the original cadmium-telluride solar panels, it was difficult to quantify since the panels themselves degraded significantly with time (4). However, the temperature of the panels was recorded continuously from June 1995 until July 2001. Then in April 2002 we began collecting data after replacing the thin-film cadmium-telluride panels with thin-film amorphous-silicon (a-Si) panels. While a-Si panels degrade about 20% initially – the degradation rates after this 20% are similar to polycrystalline silicon panels or about 1-2 % per year (6). Unfortunately, panel temperature was not recorded from April 2002 until February 2003. In February 2003 both cadmium-telluride and a-Si panel temperature were recorded using copper-constantan thermocouple wire to measure the temperature of both solar panels. Although we didn't measure the panel temperature from April 2002 to February 2003, we did periodically measure the short circuit current and open circuit voltage of individual a-Si panels and observed that the performance of the panels varied significantly between hot calm days and cold windy days (e.g. solar panel performance much better on cold windy days). We also began recording 2-m height wind speed data (at a distance of 8.5 m from the panels) in January 2003 to see if there was an effect of wind speed on solar panel temperature. The purpose of this paper is to report the solar panel performance dependence on solar panel temperature using the a-Si panels which show little sign of panel degradation after the initial decline.

2. RESULTS

2.1 Seasonal Panel Temperature Variation and the Effect on Solar-PV Performance

Fig. 1 shows the average monthly panel temperature measured at the USDA-ARS laboratory near Bushland, TX at an irradiance of 1000 W/m^2. This specific irradiance (1000 W/m^2) was selected since solar panel manufacturers rate their panels at this irradiance level. The maximum average monthly panel temperature occurs in July-August and the minimum average monthly panel temperature occurs in December-January. The one-year's worth of data with the a-Si data indicates the solar panel temperature was always a few degrees higher than the cadmium-telluride panels – these few degrees difference in panel temperature implies a 0.5-1% decrease in performance (based on manufacturer's specifications on the solar panels). The average monthly panel temperature during the period July 1995 to June 2001 is shown in Fig. 2. Also shown in Fig. 2 is the predicted performance (in percent of rated) based on the a-Si solar panel manufacturer's published sensitivity to panel temperature. Solar panels are predicted to be 100% of rated when the panel temperature is 25°C. These panels should perform about 1% above rated during December and January while during July and August they should be at around 93.5% of rated. Although the change in performance is only 7.5% for the average monthly panel temperature, if one were to compare the hottest/calm sunny day in summer to the coldest/windy sunny day in winter, the difference in performance would be about 15%.

2.2 Effect of Panel Temperature on Solar-PV Water Pumping Performance

The effect of panel temperature on a-Si panel performance is demonstrated in Figs. 3-6. Fig. 3 shows irradiance measured at the panel tilt angle (25 degrees) on a warm day (9-13-2003) and a hot day (8-1-2003) at Bushland, TX. The irradiance drops on the warm day during the time interval

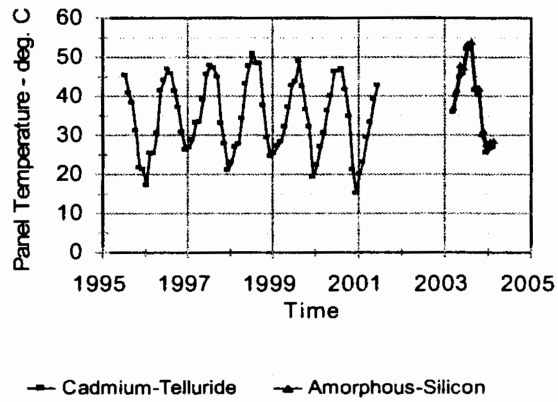

Fig. 1. Average Monthly Panel Temperature at 1000 W/m^2 at Bushland, TX.

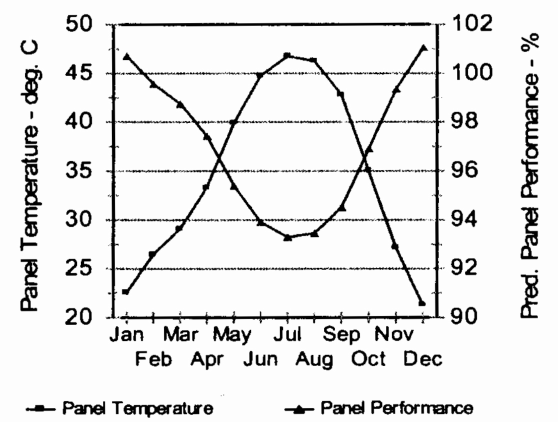

Fig. 2. Panel Temperature and Predicted Panel Performance at Bushland, TX (07/95-06/01) at 1000 W/m^2.

7:45 to 8:30 a.m. due to clouds. Irradiance is approximately the same from 9 a.m. until 3 p.m. for both the warm and hot days shown. After 3 p.m. the irradiance during a hot day is 50-100 W/m^2 higher than the warm day due to sun being higher in the sky in August compared to September. Fig. 4 shows the panel and air temperature for both the warm and hot days. The difference in panel temperature between the warm and hot days from 9 a.m. to 3 p.m. (e.g. similar irradiance) varies from 21°C to 27°C which would imply a 6.5 to 8.3 % difference in performance based on the solar panel manufacturer's published performance sensitivity to temperature for this temperature range (0.308%/°C). The difference in air temperature during this time period (9 a.m. to 3 p.m.) varied from 15°C to 18°C. It should be noted that the panel and air temperature are approximately the same when there is no radiation from the sun. Fig. 5 shows a comparison of the water flow rates for both the warm and hot days. The pump motor used was a 3-phase 230 V 0.56 kW (0.75 hp) submersible motor. The pump was a 12-stage 0.56 kW (0.75 hp) centrifugal pump. The simulated pumping depth was set to 42 m (138 ft) using a back-pressure valve. During the time period 9 a.m. to 3 p.m. (e.g. similar irradiance) the pumping performance varied from 2 to 4 l/min (approximately 0.5 to 1 gal/min). This measured performance loss (7 to 10 %) due to panel temperature increase was slightly higher than that predicted by the manufacturer (6.5 to 8.3%). Figure 6 shows the measured AC power between the controller and the pump motor for both the warm and hot days. Since the percentage change in AC power due to panel temperature is similar to the percentage change in flow rate due to panel temperature, this data corroborates the water flow rate data.

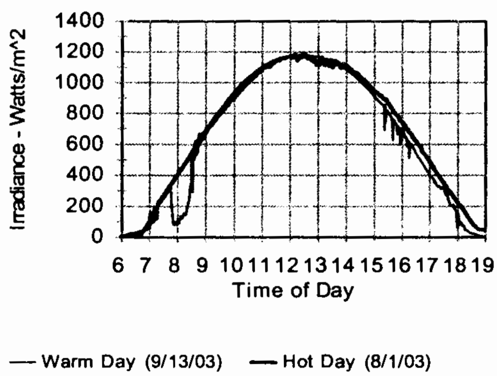

Fig. 3. Irradiance for Warm Day and Hot Day at Bushland, TX.

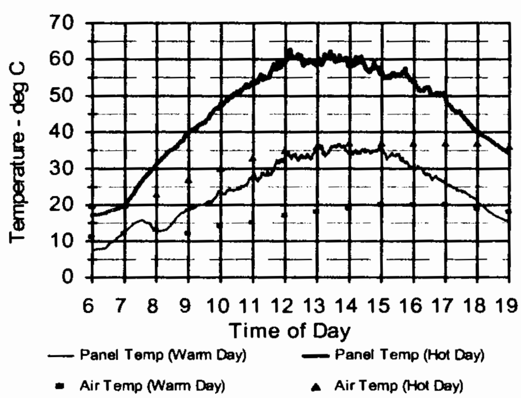

Fig. 4. Panel and Air Temperature for Warm Day and Hot Day at Bushland, TX.

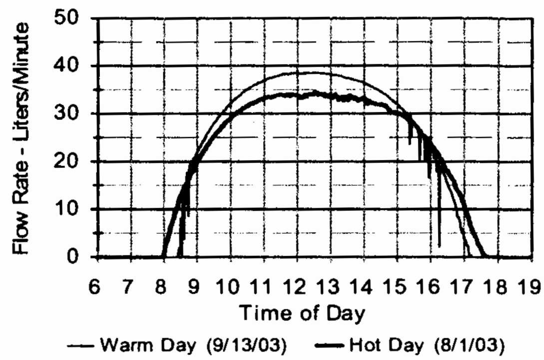

Fig. 5. Flow Rates for Warm Day and Hot Day at Bushland, TX with 42 meter head.

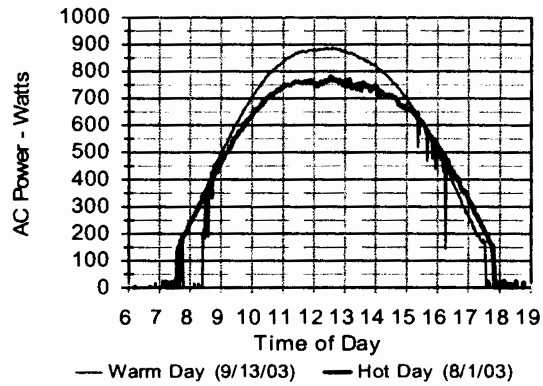

Fig. 6. AC Power for Warm Day and Hot Day at Bushland, TX with 42 meter head.

2.3 Effect of Wind Speed on Solar-PV Water Pumping Performance

While it may seem strange that wind speed would affect solar-PV water pumping performance, wind speed does affect the solar-PV performance since it affects the solar panel temperature. The wind speed was measured with a cup anemometer at a 2-m height 8.5 m from the panels in the prevailing wind direction. The irradiance of a low wind day (7-15-2003) and a moderate wind day (7-14-2003) are shown in Fig. 7. The irradiance is almost identical for both of these days except at 10:30 a.m. and 5 p.m. when a cloud causes a decrease in irradiance in the morning and an increase in irradiance in the afternoon. Clouds can cause an increase in irradiance because they can act like a reflector and actually focus the sun's radiation onto the solar panels. Fig. 8 shows how the wind speed varies during the low and moderate wind days. The wind speeds for both days are about the same at 10:30 a.m., but the wind speed for the moderate wind day is higher in the afternoon. The wind speeds for the moderate wind day averaged about 5.5 m/s (12.3 mph) in the afternoon, which is below the average wind speed for Bushland. The wind speed average for the low wind day in the afternoon was about 2 m/s (4.5 mph).

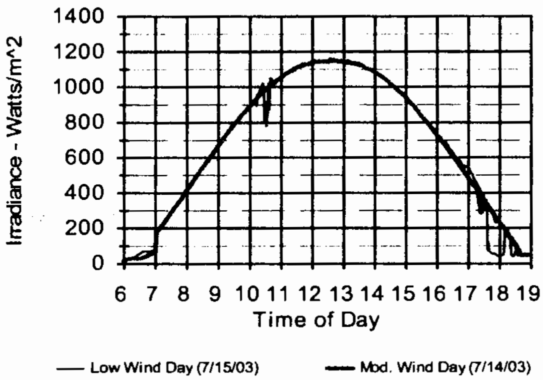

Fig. 7. Irradiance on Low Wind Day and Moderate Wind Day at Bushland, TX.

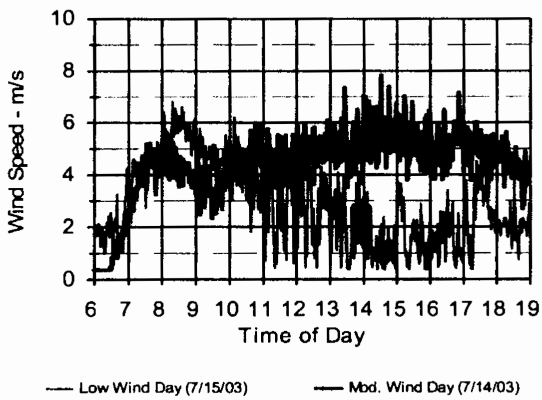

Fig. 8. Wind Speed on Low Wind Day and Moderate Wind Day at Bushland, TX.

Figure 9 shows the a-Si panel and air temperature for the low wind and moderate wind days. The air temperature from 11 a.m. to 5 p.m. is the same, so the reason for the deviation in panel temperature from 11 a.m. to 4 p.m. is entirely due to the wind cooling the panels off on the moderate wind day. After 4 p.m., the irradiance for the low wind day increases (see Fig. 7), so that will also have an effect on the panel temperature. Fig. 10 shows a comparison of the water flow rates for the low wind and moderate wind days. From 11 a.m. to 3 p.m. the low wind day has a lower flow rate than the moderate wind day. The changes in the panel temperature (Fig. 9) directly correspond to the changes in the water flow rate (Fig. 10). The difference in total water volume for the low wind and moderately windy day is only 2%. However, the water flow rate for the low wind day does exceed that of the moderate wind day at 5 p.m., but this is due to the increased irradiance for the low wind day due to the lens effect of a cloud.

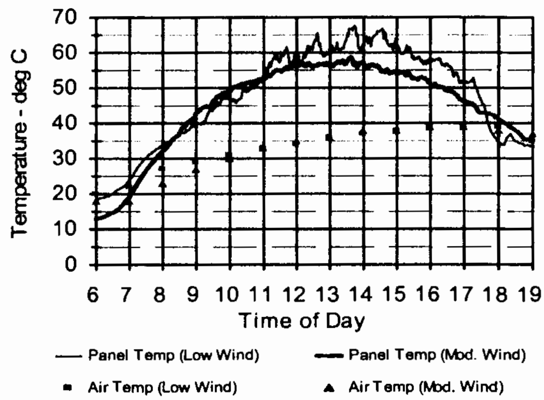

Fig. 9. Panel and Air Temperature for a Low and Moderately Windy Day at Bushland, TX.

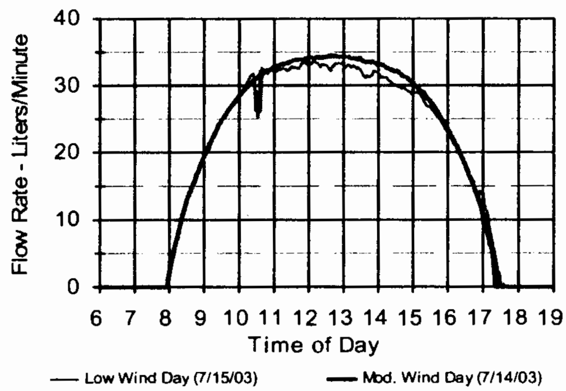

Fig. 10. Flow Rates for Low and Moderately Windy Days at Bushland, TX for 42 meter head.

2.4 Equation for Panel Temperature

While the data presented in this paper demonstrates the effects of panel temperature on performance of a-Si panel, it doesn't help other solar-PV users estimate their performance losses. Using the data we have collected over the past year, we have derived an equation that will estimate the difference between panel temperature and air temperature given measured irradiance and wind speed. Discussions with other solar energy researchers indicate that panel temperature would also be affected by relative humidity. However, in the data we have collected, we haven't seen an effect from relative humidity on solar panel temperature. Bushland, TX, is a semi-arid climate with low humidity; therefore, an effect found in wetter climates was not found in this drier climate.

A multiple regression analysis technique was used to develop the following equation to estimate the difference between panel temperature and air temperature. This equation allows a user to estimate the panel temperature if the air temperature, irradiance, and wind speed are known. The equation is:

$$\Delta T = a + bI + cW$$

Where ΔT = Panel temperature – Air temperature (°C)
I = Irradiance incident on solar panel (W/m^2)
W = Wind speed at solar panel height (m/s)
a, b, c are coefficients (see Table 1. for list of coefficients for season and irradiance level with the corresponding correlation coefficient – based on data gathered at USDA-ARS near Bushland, TX from 03/2003 to 02/2004).

The hourly air temperature should be available from most meteorological stations in the U.S. The irradiance can be estimated from a National Renewable Energy Lab (NREL) report (7) which also can be downloaded from NREL's web site (www.nrel.gov). The panel height wind speed can be estimated from another anemometer height (2-m or 10-m wind speed measurements are available at national weather stations or agricultural experiment stations) using the following power law equation:

$$V = V_o (H/H_o)^{\alpha}$$

Where V = Wind speed at height desired
V_o = Wind speed at known height
H = Height desired
H_o = Height of known anemometer
α = exponent dependent on terrain (8)

3. CONCLUSIONS

Solar panel temperature of thin-film panels was measured at Bushland, TX, for several years and the average performance change from rated (rated power at irradiance of 1000 W/m^2 and a panel temperature of 25°C and a spectral distribution of AM 1.5) was estimated at 7-10%. During the months of December and January the panel performance was measured to be 1% better than rated for an average panel temperature of 22°C, but the panel performance was measured to be 6.5% worse than rated during July and August for an average panel temperature of 47°C. Data were included to show how panel temperature would decrease (panel performance increase) when wind speed increased (e.g. wind caused convective cooling of solar panels). A set of equations was developed for estimating the increase in panel temperature from the air temperature with the only inputs being irradiance incident on panels and panel height wind speed data. While the correlation coefficients seemed somewhat low at low irradiance levels, specific days which were checked indicated the predicted and actual panel temperature differed by only a few degrees. The predicted panel performance degradation due to an increase in panel temperature was verified by data collected at Bushland, TX.

4. ACKNOWLEDGEMENTS

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5. REFERENCES

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TABLE 1. COEFFICIENTS FOR PANEL TEMPERATURE EQUATION.

Season	Irradiance W/m^2	a	B	c	Correlation Coefficient r
Spring	200	0.2	0.0261	-0.37	0.544
	400	3.9	0.0223	-0.79	0.584
	600	5.6	0.0214	-1.05	0.692
	800	9.3	0.0182	-1.31	0.756
	1000	10.6	0.0186	-1.57	0.814
	1200	14.5	0.0171	-1.87	0.842
Summer	200	0.1	0.0290	-0.43	0.505
	400	5.2	0.0211	-0.99	0.488
	600	7.4	0.0195	-1.29	0.637
	800	10.0	0.0176	-1.57	0.740
	1000	12.6	0.0161	-1.81	0.760
	1200	29.6	0.0021	-1.99	0.775
Fall	200	0.7	0.0251	-0.46	0.496
	400	3.4	0.0189	-0.82	0.530
	600	5.6	0.0181	-1.08	0.691
	800	6.9	0.0189	-1.49	0.796
	1000	6.7	0.0206	-1.79	0.844
	1200	13.3	0.0158	-2.05	0.865
Winter	200	0.2	0.0216	-0.21	0.449
	400	4.0	0.0173	-0.69	0.580
	600	4.6	0.0209	-1.15	0.714
	800	8.7	0.0207	-1.79	0.808
	1000	11.2	0.0181	-1.83	0.810
	1200	19.7	0.0121	-2.10	0.822

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